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MATERIALS AND MECHANICS OF METAMATERIAL ENHANCED MEMS FOR TERAHERTZ TECHNOLOGY

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14. ABSTRACT
Metamaterials are sub-wavelength composites where the electromagnetic response originates from oscillating electrons in highly conducting metals such as gold or copper allowing for a design specific resonant response of the electrical permittivity or magnetic permeability. This is especially important for the technologically relevant terahertz frequency regime where there is a strong need to create components to realize applications ranging from spectroscopic identification of hazardous materials to noninvasive imaging. Over the past years, Dr. Zhang, Dr. Averitt, and their team at Boston University have worked on fundamental research combining metamaterials with MEMS (microelectromechancial systems or microsystems) at terahertz frequencies. The team has developed metamaterial enhanced resonant detectors with a simple fabrication process for active terahertz sensing and detection applications. The team has published 20+ papers in top journals including Nature, Physical Review Letters, and Advanced Materials. Their work has also been highlighted by Science, Nature, and MRS Bulletin. In addition, two PhD students have won Boston University Best Dissertation Awards through working on this project.

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MATERIALS AND MECHANICS OF METAMATERIAL ENHANCED MEMS FOR TERAHERTZ TECHNOLOGY

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Final Performance Report

Xin Zhang
Boston University

BOSTON UNIVERSITY

Grant Title:	Materials and Mechanics of Metamaterial Enhanced MEMS for Terahertz Technology
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PI/Institution/Address:	Dr. Xin Zhang, Professor, Department of Mechanical Engineering, Boston University, 110 Cummington Mall, Boston, MA 02215, USA; Tel: 617-358-2702, Fax: 617-353-5866, email: xinz@bu.edu
Program Manager:	Dr. B. L. ("Les") Lee, ScD, Program Manager for Mechanics of Multifunctional Materials & Microsystems, Air Force Office of Scientific Research, 875 N. Randolph Street, AFOSR/NA, Suite 325, Room 3112, Arlington, VA 22203, USA; Tel: 703-696-8483, Fax: 703-6968451, email: Byung.Lee@us.af.mil

Abstract:

Recently, artificially structured electromagnetic materials have become an extremely active research area because of the possibility of creating materials which exhibit novel electromagnetic responses not available in natural materials, such as negative refractive index. Such electromagnetic composites, often called metamaterials, are sub-wavelength composites where the electromagnetic response originates from oscillating electrons in highly conducting metals such as gold or copper allowing for a design specific resonant response of the electrical permittivity or magnetic permeability. This is especially important for the technologically relevant terahertz frequency regime where there is a strong need to create components to realize applications ranging from spectroscopic identification of hazardous materials to noninvasive imaging. Over the past years, the PIs and their team at Boston University have worked on fundamental research combining metamaterials with MEMS (microelectromechancial systems or microsystems) at terahertz frequencies. The team has developed metamaterial enhanced resonant detectors with a simple fabrication process for active terahertz sensing and detection applications. The team has published papers in top journals including Nature, Physical Review Letters, and Advanced Materials. Their work has also been highlighted by Science, Nature, and MRS Bulletin. In addition, two PhD students have won Boston University Best Dissertation Awards through working on this project. (200 words)

Personnel:

Principal Investigator:

Dr. Xin Zhang, Professor, Department of Mechanical Engineering, Boston University, 110 Cummington Mall, Boston, MA 02215; Tel: 617-358-2702, email: xinz@bu.edu

Co-Principal Investigator:

Dr. Richard Averitt, Professor, Department of Physics, Boston University, 590 Commonwealth Ave, Boston, MA 02215 Tel: 617-353-2619, email: raveritt@physics.bu.edu

Major Ph.D. students who have worked on this project:

Hu Tao, Kebin Fan, Huseyin Seren

Major postdoctoral researchers who have worked on this project:

Harold Hwang, Kebin Fan

- *Hu Tao* graduated with a PhD degree in May 2010. His PhD thesis, entitled *MEMS Enhanced Metamaterials: Towards Filling the Terahertz Gap*, is available at Boston University Library. If you are interested in getting a copy of the thesis, please contact Prof. Xin Zhang at the address given above.
- *Kebin Fan* graduated with a PhD degree in May 2012. His PhD thesis, entitled *Three-Dimensional and Nonlinear Metamaterials at Terahertz Frequencies*, is available at Boston University Library. If you are interested in getting a copy of the thesis, please contact Prof. Xin Zhang at the address given above.

- *Huseyin Seren* will graduate with a PhD degree in May 2014. His PhD thesis, entitled *Functional Terahertz Metamaterial Perfect Absorber*, will be available at Boston University Library. If you are interested in getting a copy of the thesis, please contact Prof. Xin Zhang at the address given above.

Publications:

Archival journal publications:

Title: Comparison of Birefringent Electric Split-Ring Resonator and Meanderline Structure as Quarter-Wave Plates at Terahertz Frequencies
* With A.C. Strikwerda, K. Fan, H. Tao, D.V. Pilon, R.D. Averitt
* Published in: *Optics Express*, 2009, 17(1): 135-149

Title: Reconfigurable Terahertz Metamaterials
* With H. Tao, A.C. Strikwerda, K. Fan, W.J. Padilla, R.D. Averitt
* Published in: *Physical Review Letters*, 2009, 103(14): 147401(4pp)

Title: A Dual Band Terahertz Metamaterial Absorber
* With H. Tao, C.M. Bingham, D.V. Pilon, K. Fan, A.C. Strikwerda, D. Shrekenhamer, W.J. Padilla, R.D. Averitt
* Published in: *Journal of Physics D: Applied Physics*, 201, 43(22): 225102(5pp)

Title: Metamaterial Silk Composites at Terahertz Frequencies
* With H. Tao, J.J. Amsden, A.C. Strikwerda, K. Fan, D.L. Kaplan, R.D. Averitt, F.G. Omenetto
* Published in: *Advanced Materials*, 2010, 22(32): 3527-3531

Title: Performance Enhancement of Terahertz Metamaterials on Ultrathin Substrates for Sensing Applications
* With H. Tao, A.C. Strikwerda, M. Liu, J.P. Mondia, E. Ekmekci, K. Fan, D.L. Kaplan, W.J. Padilla, R.D. Averitt, F.G. Omenetto
* Published in: *Applied Physics Letters*, 2010, 97(26): 261909(3pp)

Title: Recent Progress in Electromagnetic Metamaterial Devices for Terahertz Applications
* With H. Tao, W.J. Padilla, R.D. Averitt
* Published in: *IEEE Journal of Selected Topics in Quantum Electronics*, 2011, 17(1): 92-101

Title: MEMS Based Structurally Tunable Metamaterials at Terahertz Frequencies
* With H. Tao, A. Strikwerda, K. Fan, W.J. Padilla, R.D. Averitt
* Published in: *Journal of Infrared, Milimeter, and Terahertz Waves*, 2011, 32(5): 580-595

Title: Frequency Tunable Terahertz Metamaterials Using Broadside Coupled Split-Ring Resonators

* With E. Ekmekci, A.C. Strikwerda, K. Fan, G. Keiser, G. Turhan-Sayan, R.D. Averitt
* Published in: *Physical Review B,* 2011, 83(19): 193103(4pp)

Title: Stand-up Magnetic Metamaterials at Terahertz Frequencies

* With K. Fan, A.C. Strikwerda, H. Tao, R.D. Averitt
* Published in: *Optics Express*, 2011, 19(13): 12619-12627

Title: Metamaterials on Paper as a Sensing Platform

* With H. Tao, L. Chieffo, M.A. Brenckle, S.M. Siebert, M. Liu, A.C. Strikwerda, K. Fan, D.L. Kaplan, R.D. Averitt, F.G. Omenetto
* Published in: *Advanced Materials*, 2011, 23(28): 3197-3201

Title: Microwave and Terahertz Wave Sensing with Metamaterials

* With H. Tao, E.A. Kadlec, A.C. Strikwerda, K. Fan, W.J. Padilla, R.D. Averitt, E.A. Shaner
* Published in: *Optics Express*, 2011, 19(22): 21620-21626

Title: Electromagnetic Composite-Based Reflecting Terahertz Waveplates

* With A.C. Strikwerda, R.D. Averitt, K. Fan, G.D. Metcalfe, M. Wraback
* Published in*: International Journal of High Speed Electronics and Systems*, 2011, 20(3): 583-588

Title: Extremely Thin Metamaterial as Slab Waveguide at Terahertz Frequencies

* With Y. Minowa, M. Nagai, H. Tao, K. Fan, A.C. Strikwerda, R.D. Averitt, K. Tanaka
* Published in: *IEEE Transactions on Terahertz Science and Technology*, 2011, 1(2): 441-449

Title: Flexible Metamaterial Absorbers for Stealth Applications at Terahertz Frequencies

* With K. Iwaszczuk, A.C. Strikwerda, K. Fan, R.D. Averitt, P. Uhd Jepsen
* Published in: *Optics Express*, 2012, 20(1): 635-643

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* With W.-C. Chen, A. Totachawattana, K. Fan, J.L. Ponsetto, A.C. Strikwerda, R.D. Averitt, W.J. Padilla
* Published in: *Physical Review B*, 2012, 85(3): 035112(6pp)

Title: Three-Dimensional Magnetic Terahertz Metamaterials Using a Multilayer Electroplating Technique

* With K. Fan, A.C. Strikwerda, R.D. Averitt
* Published in: *Journal of Micromechanics and Microengineering*, 2012, 22(4): 045011(9pp)

Title: Time-Resolved Imaging of Near-Fields in THz Antennas and Direct Quantitative Measurement of Field Enhancements
* With C.A. Werley, K. Fan, A.C. Strikwerda, S.M. Teo, R.D. Averitt, K.A. Nelson
* Published in: *Optics Express*, 2012, 20(8): 8551-8567

Title: THz Near-Field Faraday Imaging in Hybrid Metamaterials
* With N. Kumar, A.C. Strikwerda, K. Fan, R.D. Averitt, P.C.M. Planken, and A.J.L. Adam
* Published in: *Optics Express*, 2012, 20(10): 11277-11287

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* With M. Liu, H.Y. Hwang, H. Tao, A.C. Strikwerda, K. Fan, G.R. Keiser, A.J. Sternbach, K.G. West, S. Kittiwatanakul, J. Lu, S.A. Wolf, F.G. Omenetto, K.A. Nelson, R.D. Averitt
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* With K. Fan, A.C. Strikwerda, R.D. Averitt
* Published in: *Physical Review B - Rapid Communications*, 2013, 87(16): 161104(4pp)

Title: Nonlinear Terahertz Metamaterials via Field-Enhanced Carrier Dynamics in GaAs
* With K. Fan, H.Y. Huang, M. Liu, A.C. Strikwerda, A. Sternback, J. Zhang, X. Zhao, K.A. Nelson, R.D. Averitt
* Published in: *Physical Review Letters*, 2013, 110(21): 217404(5pp)

Title: Decoupling Crossover in Asymmetric Broadside Coupled Split Ring Resonators at Terahertz Frequencies
* With G.R. Keiser, A.C. Strikwerda, K. Fan, V. Young, R.D. Averitt
* Published in: *Physical Review B*, 2013, 88(2): 024101(5pp)

Title: Towards Dynamic, Tunable, and Nonlinear Metamaterials via Near Field Interactions: A Review
* With G.R. Keiser, K. Fan, R.D. Averitt
* Published in: *Journal of Infrared, Millimeter, and Terahertz Waves*, 2013, 34(11): 709-723

Title: Optically Tunable Terahertz Metamaterials on Highly Flexible Substrates
* With K. Fan, X. Zhao, J. Zhang, G.R. Keiser, H.R. Seren, G.D. Metcalfe, M. Wraback
* Published in: *IEEE Transactions on Terahertz Science and Technology*, 2013, 3(6): 702-708

Conference proceeding papers:

- H. Tao, N.I. Landy, K. Fan, A.C. Strikwerda, W.J. Padilla, R.D. Averitt, and X. Zhang, "Terahertz Metamaterials with Simultaneously Negative Electric and Magnetic Resonance

Responses Based on Bimaterial Pop up Structures," *Proceeding of the 22nd IEEE International Conference on Micro Electro Mechanical Systems (MEMS '09)*, Sorrento, Italy, January 25-29, 2009, pp. 108-111.

- K. Fan, A.C. Strikwerda, H. Tao, W.J.Padilla, R.D. Averitt, and X. Zhang, "3D Standup Metamaterials with Purely Magnetic Resonance at Terahertz Frequencies," *Proceeding of the 23rd IEEE International Conference on Micro Electro Mechanical Systems (MEMS '10)*, Hong Kong, China, January 24-28, 2010, pp. 843-846.

- H. Tao, J.J. Amsden, A.C. Strikwerda, K. Fan, D.L. Kaplan, F.G. Omenetto, R.D. Averitt, and X. Zhang, "Large Area Spraying of Terahertz Metamaterials on Free-Standing Biocompatible Silk Films," *Technical Digest of IEEE Solid-State Sensor and Actuator Workshop (Hilton Head '10)*, Hilton Head Island, SC, USA, June 6-10, 2010, pp. 138-141.

- K. Fan, A.C. Strikwerda, H. Tao, R.D. Averitt, and X. Zhang, "Broadband Tunable 3D Metamaterials at Terahertz Frequencies," *Proceeding of the 24th IEEE International Conference on Micro Electro Mechanical Systems (MEMS '11)*, Cancun, Mexico, January 23-27, 2011, pp. 680-683.

- K. Fan, A.C. Strikwerda, R.D. Averitt, and X. Zhang, "Bottom-Up Three Dimensional Metamaterials at Terahertz Frequencies," *Proceeding of the 16th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers '11)*, Beijing, China, June 5-9, 2011, pp. 2662-2665.

- H. Tao, E.A. Kadlec, A.C. Strikwerda, K. Fan, W.J. Padilla, R.D. Averitt, E.A. Shaner, and X. Zhang, "MEMS and Metamaterial-Based Terahertz Detector," *Technical Digest of IEEE Solid-State Sensor and Actuator Workshop (Hilton Head '12)*, Hilton Head Island, SC, USA, June 3-7, 2012, pp. 320-323.

- K. Fan, X. Zhao, J. Zhang, G.D. Metcalfe, R.D. Averitt, and X. Zhang, "Flexible and Tunable Metamaterials at Terahertz Frequencies," *Proceeding of the 17th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers '13)*, Barcelona, Spain, June 16-20, 2013, pp. 2225-2228.

- H.R. Seren, A.C. Strikwerda, L. Cao, G.R. Keiser, J. Zhang, K. Fan, G.D. Metcalfe, M. Wraback, R.D. Averitt, and X. Zhang, "An Optically Tunable Terahertz Perfect Absorber," *Proceeding of the 17th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers '13)*, Barcelona, Spain, June 16-20, 2013, pp. 1428-1431.

- X. Zhao, K. Fan, J. Zhang, H.R. Seren, R.D. Averitt, and X. Zhang, "Design, Fabrication and Characterization of Tunable Perfect Absorber on Flexible Substrate," *Proceeding of the 27th IEEE International Conference on Micro Electro Mechanical Systems (MEMS '14)*, San Francisco, CA, USA, January 26-30, 2014, pp. -.

Abstract referred conference presentations:

- H. Tao, et al, "Reconfigurable Terahertz Metamaterials," *Presented at the APS March Meeting 2010*, Portland, OR, March 15-19, 2010.
- H. Tao, et al, "Structurally Reconfigurable Metamaterials at Terahertz Frequencies," *Presented at the 30th Conference on Lasers and Electro-Optics*, San Jose, CA, May 18-20, 2010.
- K. Fan, et al, "3D Stand-up Metamaterials with a Purely Magnetic Resonance at Terahertz Frequencies," *Presented at the 30th Conference on Lasers and Electro-Optics*, San Jose, CA, May 18-20, 2010.
- K. Fan, et al, "A Tunable 3D Terahertz Metamateiral," *Presented at the International Workshop on Optical Terahertz Science and Technology*, Santa Barbara, CA, March 13-17, 2011.
- A.C. Strikwerda, K. Fan, et al, "Electromagnetic Composite-Based Reflecting Terahertz Waveplates," *Presented at the International Workshop on Optical Terahertz Science and Technology*, Santa Barbara, CA, March 13-17, 2011.
- K. Iwaszczuk, K. Fan, et al, "Stealth Metamaterial Objects Characterized in the Far Field by Radar Cross Section Measurements," *Presented at the International Workshop on Optical Terahertz Science and Technology*, Santa Barbara, CA, March 13-17, 2011.
- E. Ekmekci, A.C. Strikwerda, K. Fan, et al, "Frequency Tunable Metamaterial Designs Using Near-Field Coupled SRR Structures in the Terahertz Region," *Presented at the 31st Conference on Lasers and Electro-Optics*, Baltimore, MD, May 1-6, 2011.
- A.C. Strikwerda, H. Tao, E.A. Kadlec, K. Fan, et al, "Metamaterial Based Terahertz Detector," *Presented at the 31st Conference on Lasers and Electro-Optics*, Baltimore, MD, May 1-6, 2011.
- K. Fan, et al, "Tunable Terahertz 3D Metamaterials," *Presented at the 31st Conference on Lasers and Electro-Optics*, Baltimore, MD, May 1-6, 2011.
- K. Fan, et al, "A Broadband Tunable Three Dimensional Metamaterial at Terahertz Frequencies," *Presented at the 5th International Conference on Surface Plasmon Photonics*, Busan, Korea, May 15-20, 2011.
- A.C. Strikwerda, H. Tao, E.A. Kadlec, K. Fan, et al, "Metamaterial Based Terahertz Detector," *Presented at the 5th International Conference on Surface Plasmon Photonics*, Busan, Korea, May 15-20, 2011.
- E. Ekmekci, A.C. Strikwerda, K. Fan, et al, "Frequency Tunable Metamaterial Designs Using Near Field Coupled SRR Structures in the Terahertz Region," *Presented at the 36th International Conference on Infrared, Millimeter, and Terahertz Waves*, Houston, TX, October 2-7, 2011.
- A.C. Strikwerda, H. Tao, E.A. Kadlec, K. Fan, et al, "Metamaterial Based Terahertz Detector," *Presented at the 36th International Conference on Infrared, Millimeter, and Terahertz Waves*, Houston, TX, October 2-7, 2011.
- K. Fan, A.C. Strikwerda, H. Tao, et al, "A Tunable 3D Terahertz Metamaterial," *Presented at the 36th International Conference on Infrared, Millimeter, and Terahertz Waves*, Houston, TX, October 2-7, 2011.

- N. Kumar, A.C. Strikwerda, K. Fan, et al, "Direct Measurement of the THz Near-Magnetic Field of Metamaterials," *Presented at the 36th International Conference on Infrared, Millimeter, and Terahertz Waves*, Houston, TX, October 2-7, 2011.
- M. Liu, H.Y. Hwang, H. Tao, A.C. Strikwerda, K. Fan, et al, "THz Induced Insulator to Metal Transition in VO2 Metamaterial," *Presented at the APS March Meeting 2012*, Boston, MA, February 27 - Mach 2, 2012.
- J. Zhang, K. Fan, et al, "Oxygen Vacancy Induced Metal Insulator Transition in Epitaxial Pr0:7Ca0:3MnO3 Thin Films," *Presented at the APS March Meeting 2012*, Boston, MA, February 27 - Mach 2, 2012.
- L. Chieffo, G.R. Keiser, A.C. Strikwerda, K. Fan, et al, "Metamaterial Enhanced Terahertz Spectroscopy of Biomolecules," *Presented at the APS March Meeting 2012*, Boston, MA, February 27 - Mach 2, 2012.
- K. Fan, H.Y. Hwang, et al, "Nonlinear Metamaterials through Enhanced Impact Ionization in GaAs at Terahertz Frequencies," *Presented at the APS March Meeting 2012*, Boston, MA, February 27 - Mach 2, 2012.
- G.R. Keiser, A.C. Strikwerda, K. Fan, et al, "Bianisotropy Compensation in Metamaterials," *Presented at the APS March Meeting 2012*, Boston, MA, February 27 - Mach 2, 2012.
- A.C. Strikwerda, H. Tao, E.A. Kadlec, K. Fan, et al, "Metamaterial Based Terahertz Detector," *Presented at the APS March Meeting 2012*, Boston, MA, February 27 - Mach 2, 2012.
- G.D. Metcalfe, M. Wraback, A.C. Strikwerda, K. Fan, et al, "Terahertz Polarimetry Based on Metamaterial Devices," *Presented at the SPIE Defense, Security, and Sensing*, Baltimore, MD, April 23-27, 2012.
- N. Kumar, A.C. Strikwerda, K. Fan, et al, "THz Near-Field Faraday Imaging in Hybrid Metamaterials," *Presented at the 3rd EOS Topical Meeting on Terahertz Science & Technology*, Prague, Czech Republic, June 17-20, 2012.
- H.Y. Hwang, M. Liu, K. Fan, et al, "Metamaterial-Enhanced Nonlinear Terahertz Spectroscopy," *Presented at the XVIIIth International Conference on Ultrafast Phenomena*, Lausanne, Switzerland, July 8-13, 2012.
- H.Y. Hwang, et al, "Nonlinear Terahertz Spectroscopy," *Presented at the International Symposium on Frontiers in THz Technology*, Nara, Japan, November 27-29, 2012.
- H. Seren, et al, "Nonlinear THz Plamonic Disk Resonators," *Presented at the APS March Meeting 2013*, Baltimore, MD, Mach 18-22, 2013.
- G.R. Keiser, H. Seren, et al, "Controlling Metamaterial Field Enhancement at Terahertz Frequencies," *to be presented at the APS March Meeting 2013*, Baltimore, MD, Mach 18-22, 2013.
- S.M. Teo, C.A. Werley, C. Wang, K. Fan, et al "Visualization of THz Fields in an ITO Metallic Slab Waveguide," *Presented at the International Workshop on Optical Terahertz Science and Technology*, Kyoto, Japan, April 1-5, 2013.
- H.Y. Hwang, K. Fan, et al, "Metamaterial-Enhanced Nonlinear Responses in Semiconductors as a THz Detection Platform," *Presented at the International Workshop on Optical Terahertz Science and Technology*, Kyoto, Japan, April 1-5, 2013.

- N.C. Brandt, H.Y. Hwang, K. Fan, et al, "THz-Induced Decomposition of Organic Crystalline Materials," *Presented at the International Workshop on Optical Terahertz Science and Technology*, Kyoto, Japan, April 1-5, 2013.
- N.C. Brandt, H.Y. Hwang, K. Fan, et al, "Nonlinear 2D and 3D Metamaterials on Silicon," *Presented at the International Workshop on Optical Terahertz Science and Technology*, Kyoto, Japan, April 1-5, 2013.
- E. Abreu, J. Zhang, S. Wang, K. Fan, H.Y. Hwang, et al, "VO2 and V2O3: Different Phase Transition Pathways Probed by THz Spectroscopy," *Presented at the International Workshop on Optical Terahertz Science and Technology*, Kyoto, Japan, April 1-5, 2013.
- H.Y. Hwang, K. Fan, et al, "Metamaterial-Enhanced Nonlinear Responses in Semiconductors as a THz Detection Platform," *Presented at the 2013 Conference on Lasers and Electro-Optics*, San Jose, CA, June 9-14, 2013.
- H.Y. Hwang, K. Fan, et al, "Metamaterial-based Terahertz Detectors," *Presented at the Optical Sensors - 2013 OSA Topical Meeting*, Rio Grande, Puerto Rico, July 14-17, 2013.
- H.Y. Hwang, et al, "Terahertz Responses in Oxides: Nonlinear Effects and Engineered Structures," *Presented at the 8th International Workshop on Multifunctional Materials*, Itamambuca, Brazil, November 10-14, 2013.

Ph.D. Dissertations:

- Hu Tao, "MEMS Enhanced Metamaterials: Towards Filling the Terahertz Gap," Ph.D. Dissertation, May 2010. (Boston University Engineering Best Dissertation Award)
- Kebin Fan, "Three-Dimensional and Nonlinear Metamaterials at Terahertz Frequencies," Ph.D. Dissertation, May 2012. (Boston University Mechanical Engineering Best Dissertation Award)
- Huseyin Seren, "Functional Terahertz Metamaterial Perfect Absorber," Ph.D. Dissertation, expecting May 2014.

Honors/Awards/Special Recognition:

- PhD student Hu Tao received the most prestigious student award issued by the Chinese government: the National Award for Outstanding Overseas Chinese Students (Spring 2010).
- PhD student Hu Tao won 2010 Boston University Engineering Best Dissertation Award (MEMS Enhanced Metamaterials: Towards Filling the Terahertz Gap, May 2010, Advisor: Xin Zhang).
- Our work became Insider Front Cover of Advanced Materials (Vol. 22, August 2010).
- Our work became Journal of Physics D: Applied Physics - Highlights of 2010 (A Dual Band Terahertz Metamaterial Absorber, January 2011).
- Our work won Best Poster Award at the Fifth International Conference on Surface Plasmon Photonics (May 2011)
- Dr. Xin Zhang is selected to participate in National Academy of Engineering's E.U.-U.S. Engineering Symposium (November 2011).

- Our work is highlighted by Science (Metamaterials to See in THz, Vol. 334, 18 November 2011).
- Our work became Cover of Journal of Micromechanics & Microengineering (Vol. 22, April 2012).
- PhD student Kebin Fan won 2012 Mechanical Engineering Outstanding PhD Dissertation Award (Three-Dimensional and Nonlinear Metamaterials at Terahertz Frequencies, May 2012, Advisor: Xin Zhang).
- Our work is highlighted by ars technical (A Golden Antenna Turns an Insulator into a Metal, July 16, 2012)
- Our work is highlighted by Science Daily (Terahertz Radiation Can Induce Insulator-To-Metal, July 25, 2012)
- Our work is chosen to be displayed on the front page of Physical Review B (April 2013).
- Our work won Best Poster Award at International Workshop on Optical Terahertz Science and Technology (April 2013).

Accomplishments:

(summarized basing on archival journal publications)

Comparison of Birefringent Electric Split-Ring Resonator and Meanderline Structure as Quarter-Wave Plates at Terahertz Frequencies
Optics Express, 2008, 17(1): 136-149

Abstract: We have fabricated a quarter-wave plate from a single layer of birefringent electric split-ring resonators (ELC). For comparison, an appropriately scaled double layer meanderline structure was fabricated. At the design frequency of 639 GHz, the ELC structure achieves 99.9% circular polarization while the meanderline achieves 99.6%. The meanderline displays a larger bandwidth of operation, attaining over 99% circular polarization from 615 - 743 GHz, while the ELC achieves 99% from 626 - 660 GHz. However, both are broad enough for use with CW sources making ELCs a more attractive choice due to the ease of fabrication. Both samples are free standing with a total thickness of 70 μm for the meanderline structure and a mere 20 μm for the ELC highlighting the large degree of birefringence exhibited with metamaterial structures.

Conclusion: In conclusion, we have fabricated and tested meanderline and ELC THz quarter-wave plates. While the traditional meanderline is superior in bandwidth and magnitude of transmission, the ELC is easier to fabricate since it consists of only one active Au layer, has a more consistent phase shift, and a greater peak polarization percentage. Specifically, the ELC achieves 99.8% circular polarization at the designed frequency, with a broad enough bandwidth for use with CW sources.

Reconfigurable Terahertz Metamaterials
Physical Review Letters, 2009, 103(14): 147401(4pp)

Abstract: We demonstrate reconfigurable anisotropic metamaterials at terahertz frequencies where artificial ‘‘atoms’’ reorient within unit cells in response to an external stimulus. This is accomplished by fabricating planar arrays of split ring resonators on bimaterial cantilevers designed to bend out of plane in response to a thermal stimulus. We observe a marked tunability of the electric and magnetic response as the split ring resonators reorient within their unit cells. Our results demonstrate that adaptive metamaterials offer significant potential to realize novel electromagnetic functionality ranging from thermal detection to reconfigurable cloaks or absorbers.

Conclusion: Our experimental and simulation results reveal that it is possible to create reconfigurable metamaterials where re-orientation of the SRRs leads to a tunable electromagnetic response that is dominantly electric or magnetic in nature. For these initial proof-of-principle measurements, RTA was used to lock the SRRs into a set orientation. This facilitated electromagnetic characterization using THz-TDS. However, in actual operation, it will be possible to actively reorient the SRRs using well-developed actuation techniques which include resistive, piezoelectric, and electrostatic actuation. Potential applications include reconfigurable filters, negative index surfaces, thermal cantilever-based detection, or fine tuning of the electric or magnetic response for optimizing perfect absorbers or transformation optics derived metamaterials such as cloaks or concentrators. Furthermore, in the present demonstration of reconfigurable MMs, each of the SRRs was designed to reorient in an identical fashion in response to an external stimulus. More complex materials could be designed where a fraction of the unit cells remain stationary or different unit cells move in orthogonal directions.

A Dual Band Terahertz Metamaterial Absorber
Journal of Physics D: Applied Physics, 2010, 43(22): 225102(5pp)

Abstract: We present the design, fabrication and characterization of a dual band metamaterial absorber which experimentally shows two distinct absorption peaks of 0.85 at 1.4 THz and 0.94 at 3.0 THz. The dual band absorber consists of a dual band electric-field-coupled (ELC) resonator and a metallic ground plane, separated by an 8 μm dielectric spacer. Fine tuning of the two absorption resonances is achieved by individually adjusting each ELC resonator geometry.

Conclusion: In summary, a dual band terahertz metamaterial absorber consisting of two single ELC resonators combined together and a metallic ground plane, separated by a dielectric spacer, has been demonstrated. Two distinct resonant absorption peaks at 1.4 and 3.0 THz were experimentally observed, and the two absorption peaks can be individually tuned by optimizing the corresponding single ELC resonator's geometries

Metamaterial Silk Composites at Terahertz Frequencies
Advanced Materials, 2010, 22(32): 3527-3531

Abstract: In this communication we report the fabrication and characterization of the first large area metamaterials structures patterned on free-standing biocompatible silk substrates showing strong resonance responses at terahertz frequencies, providing a promising path towards the development a new class of metamaterial-inspired bioelectric and biophotonic devices. A broad swath of the electromagnetic spectrum is of potential interest for such applications. However, in this letter we focus on metamaterial silk composites which are resonant at the technologically relevant terahertz frequency regime (1 THz = 10^{12} Hz) where numerous chemical and biological agents show unique "fingerprints", which could potentially be used for identification and bio-sensing.

Conclusion: In conclusion, we provide a simple methodology to directly spray large area metamaterial structures on biocompatible silk substrates which exhibit strong resonances at desired frequencies, opening opportunities for new bioelectric and biophotonic applications including in vivo bio-tracking, bio-mimicry, silk electronics, and implantable biosensor and biodetectors. Furthermore, our results are not limited to THz frequencies and should find applications over a large swath of the electromagnetic spectrum.

Performance Enhancement of Terahertz Metamaterials on Ultrathin Substrates for Sensing Applications
Applied Physics Letters, 2010, 97(26): 261909(3pp)

Abstract: We design, fabricate, and characterize split-ring resonator (SRR) based planar terahertz metamaterials (MMs) on ultrathin silicon nitride substrates for biosensing applications. Proof-of-principle demonstration of increased sensitivity in thin substrate SRR-MMs is shown by detection of doped and undoped protein thin films (silk fibroin) of various thicknesses and by monitoring transmission changes using terahertz time-domain spectroscopy. SRR-MMs fabricated on thin film substrates show significantly better performance than identical SRR-MMs fabricated on bulk silicon substrates paving the way for improved biological and chemical sensing applications.

Conclusion: In summary, we have designed, fabricated, and characterized planar terahertz MMs on ultrathin SiNx films and bulk Si substrates for label-free biosensing applications and show agreement between experiment and simulation. MMs fabricated on thin film SiNx substrates show significantly enhanced sensitivity when compared to their counterparts fabricated on bulk

Si substrates. Such devices are scalable beyond the terahertz regime and may be potentially extended to other frequencies adding utility to this approach.

Recent Progress in Electromagnetic Metamaterial Devices for Terahertz Applications
IEEE Journal of Selected Topics in Quantum Electronics, 2011, 17(1): 92-101

Abstract: Recent advances in metamaterials (MMs) research have highlighted the possibility to create novel devices with unique electromagnetic (EM) functionality. Indeed, the power of MMs lies in the fact that it is possible to construct materials with a user-designed EM response at a precisely controlled target frequency. This is especially important for the technologically relevant terahertz (THz) frequency regime with a view toward creating new component technologies to manipulate radiation in this hard to access wavelength range. Considerable progress has been made in the design, fabrication, and characterization of MMs at THz frequencies. This article reviews the latest trends in THz MM research.

Conclusion: The utilization of and implementation of MMs at THz frequencies holds great promise for advancing applications in this technologically relevant region of the EM spectrum. THz EM MMs have attracted enormous attention and intensive research efforts, and a number of practical MM-based THz devices have been developed, including filters, absorbers, QWPs, switches, and modulators. In many cases, the MM-based THz devices outperform their conventional counterparts, though in many cases such conventional counterparts do not exist at THz frequencies. Though most MM devices operate over a narrow spectral band due to their resonant nature, efforts have been put in making devices with frequency tunability and multiple/broadband functionality, which are favored for applications employing CW THz sources/detectors. New fabrication techniques, advanced near-field characterization and novel MM designs have lead to dramatic advances during the past five years. There will be certain additional fundamental advances during the next decade coupled with the implementation of MMs into real-world THz applications.

MEMS Based Structurally Tunable Metamaterials at Terahertz Frequencies
Journal of Infrared, Milimeter, and Terahertz Waves, 2011, 32(5): 580-595

Abstract: We present the design, simulation, fabrication and characterization of structurally tunable metamaterials showing a marked tunability of the electric and magnetic responses at terahertz frequencies. Our results demonstrate that structurally tunable metamaterials offer significant potential to realize novel electromagnetic functionality ranging from dynamical filtering to reconfigurable cloaks or detectors. Furthermore, this approach is not limited to terahertz frequencies and may be readily used over much of the electromagnetic spectrum.

Conclusion: In this paper, we present a novel approach to dynamically control the electromagnetic responses of metamaterials realized by mechanically tuning the “meta-lattice structure”. Our experimental and simulation results reveal that it is possible to create structurally tunable metamaterials where reorientation of the SRRs within the unit cell leads to a tunable electromagnetic response that is dominantly electric or magnetic in nature. Bianisotropic behaviors of SRRs are also discussed for better understanding the functional mechanism of SRR based metamaterials. For these initial proof-of-principle measurements, RTA was used to lock the SRRs into a set orientation which facilitated the electromagnetic characterization using THz-TDS. However, it will be possible to actively reorient the SRRs using well-developed micro/nano actuation techniques which include thermal resistive, piezoelectric, and electrostatic actuation. The structural reconfiguration time can be on the order of milliseconds given the mechanical and thermal response times of the cantilevers. In addition, the cantilever mechanical resonance frequency is several kHz which will not substantively interfere with many potential applications which includes reconfigurable filters, negative index surfaces, thermal cantilever-based detection, or fine tuning of the electric or magnetic response for optimizing perfect absorbers or transformation optics derived metamaterials such as cloaks or concentrators. Furthermore, more complex materials could be designed where a fraction of the unit cells remain stationary or different unit cells move in orthogonal directions. The approach of tuning the “meta-lattice structure”, combined together with currently available tuning technologies of the “meta-atoms”, will provide a full understanding and control of electromagnetic MMs. Myriad possibilities exist. Finally, as with other MMs, our structurally tunable MMs are not constrained to operation at THz frequencies. There are certain to be exciting applications which extend into the infrared and visible regions of the EM spectrum.

Frequency Tunable Terahertz Metamaterials Using Broadside Coupled Split-Ring Resonators
Physical Review B, 2011, 83(19): 193103(4pp)

Abstract: We present frequency tunable metamaterial designs at terahertz (THz) frequencies using broadside coupled split-ring resonator (BC-SRR) arrays. Frequency tuning, arising from changes in near-field coupling, is obtained by in-plane displacement of the two SRR layers. For electrical excitation, the resonance frequency continuously redshifts as a function of displacement. The maximum frequency shift occurs for vertical displacement of half a unit cell, resulting in a shift of 663 GHz (51% of f_0). We discuss the difference in the BC-SRR response for electrical excitation in comparison to magnetic excitation in terms of hybridization arising from inductive and capacitive coupling.

Conclusion: In conclusion, we have investigated the effect of near-field coupling in electrically excited BC-SRR arrays. We have demonstrated an electrically excited structure that is amenable to creating mechanically actuated frequency agile metamaterials, demonstrated by an experimental resonance shift of over 50% of the center frequency. Further, we have highlighted the substantial differences in the electromagnetic response that arise for electrical excitation in comparison to the differences in the magnetic excitation that naturally arise from hybridization. Our results demonstrate the use of structural tunability under electrical excitation, and highlight the significance of near-field coupling of SRRs for future metamaterial applications.

Stand-up Magnetic Metamaterials at Terahertz Frequencies
Optics Express, 2011, 19(13): 12619-12627

Abstract: We present a detailed study of non-planar or ‘stand-up’ split ring resonators operating at terahertz frequencies. Based on a facile multilayer electroplating fabrication, this technique can create large area split ring resonators on both rigid substrates and conformally compliant structures. In agreement with simulation results, the characterization of these metamaterials shows a strong response induced purely by the magnetic field. The retrieved parameters also exhibit negative permeability values over a broad frequency span. The extracted parameters exhibit bianisotropy due to the symmetry breaking of the substrate, and this effect is investigated for both single and broad side coupled split rings. Our 3D metamaterial examples pave the way towards numerous potential applications in the terahertz region of the spectrum.

Conclusion: In summary, using a multilayer electroplating technique, we have successfully demonstrated 3D metamaterials at THz frequencies. This technique can create metamaterials on silicon and flexible polyimide, and broadside-coupled SRRs. Under the normal incidence, these metamaterials are magnetically excited and show a negative permeability over a broad band. The parameters retrieval also shows a substrate induced bianisotropic response, which is highly dependent on the substrate permittivity. Our approach enables fabrication of complex 3D metamaterials and can be easily extended to numerous other structures.

Metamaterials on Paper as a Sensing Platform
Advanced Materials, 2011, 23(28): 3197-3201

Abstract: In this paper, we introduce a paper-based metamaterial (MM) device, which can be potentially utilized for quantitative analysis in biochemical sensing applications. Planar metallic resonators with minimum features of less than 5 μm have been fabricated on paper, using a photoresist-free shadow mask deposition technique. The fabricated paper MM devices show unique electromagnetic (EM) resonant responses at predefined frequencies, which depend on the resonator size (i.e., terahertz frequencies in the current case, where 1 THz = 10^{12} Hz) and could be utilized as a signature for biochemical sensing applications. Proof-of-concept demonstrations were accomplished by monitoring the resonance shift induced by placing different concentrations of glucose solution on the paper MMs.

Conclusion: Inexpensive paper-based sensing kits already play an important role in ready-to-use diagnostics. The inclusion of easily patterned resonant electromagnetic structures adds versatility to the platform in support of an increasing number of applications. Though paper-based MMs reported in this work were designed to be functional at THz frequencies where many materials such as volatile chemicals and DNA exhibit unique EM fingerprints, they can be readily extended to other regions of the EM spectrum by simply scaling the SRR sizes and utilizing appropriately matched readout systems. In conclusion, we successfully patterned micrometer-sized MM resonators on paper substrates using shadow mask deposition techniques, showing controlled EM responses at THz frequencies. Preliminary results of glucose sensing using paper-based MMs showed sensitivity of $\approx$14.3 GHz/mmol L^{-1} with a characterization system associated ability to measure glucose level of $\approx$0.35 mmol L^{-1}, which can be further improved by optimizing the SRR geometries and the characterization system.

Microwave and Terahertz Wave Sensing with Metamaterials
Optics Express, 2011, 19(22): 21620-21626

Abstract: We have designed, fabricated, and characterized metamaterial enhanced bimaterial cantilever pixels for far-infrared detection. Local heating due to absorption from split ring resonators (SRRs) incorporated directly onto the cantilever pixels leads to mechanical deflection which is readily detected with visible light. Highly responsive pixels have been fabricated for detection at 95 GHz and 693 GHz, demonstrating the frequency agility of our technique. We have obtained single pixel responsivities as high as 16,500 V/W and noise equivalent powers of 10^{-8} W/$Hz^{1/2}$ with these first-generation devices.

Conclusion: In summary, we have developed metamaterial enhanced resonant detectors with a simple fabrication process for active THz sensing and detection applications. While we demonstrated detection at 95 GHz and 693 GHz, in principle this approach can be applied to other unconventional wavelengths where nature does not provide us with appropriate material resonances amenable to integration with thermal detection platforms. The implementation of low cost thin film THz absorbers could enable rapid progress in extending the many benefits of uncooled thermal imaging devices to the THz portion of the spectrum.

Electromagnetic Composite-Based Reflecting Terahertz Waveplates
International Journal of High Speed Electronics & Systems, 2011, 20(3): 583-588

Abstract: We have created a low profile, high efficiency half waveplate for operation at terahertz (THz) frequencies. The waveplate is a periodic gold/polyimide composite with a physical thickness of λ/10. Our reflection based waveplate has an intensity throughput of 80% at the design frequency of 350 GHz. This is quite high in comparison to transmissive THz components which typically suffer a large insertion loss due to Fresnel reflections. Simulations suggest a halfwave rotation of over 99% of the reflected THz radiation from 320 – 372 GHz. Experiments at 350 GHz confirm the basic operation of our electromagnetic composite as a functional half waveplate.

Conclusion: In conclusion, we have designed a functional reflection-based THz waveplate that, in comparison to previous transmissive waveplates, exhibits an increased intensity throughput efficiency (80% in comparison to 50%) while simultaneously doubling the induced phase shift resulting in a functional half waveplate with a center frequency of 350GHz. More generally, it is our belief that designing THz components in reflection will provide an avenue for lower loss THz components.

Extremely Thin Metamaterial as Slab Waveguide at Terahertz Frequencies
IEEE Transactions on Terahertz Science and Technology, 2011, 1(2): 441-449

Abstract: We investigate the waveguiding properties of a planar metamaterial slab using terahertz time-domain attenuated total reflection spectroscopy. The enhancement of evanescent waves is observed for transverse electric and transverse magnetic excitation and is caused by resonant excitation of waveguide modes in the slab. Our calculation describes the experimental results and justifies the extremely small effective thickness. We also studied the dispersion relations of the waveguide modes of the slab by theoretical calculation.

Conclusion: We proposed a novel method of studying the waveguiding properties of a planar metamaterial slab on a substrate using THz TD-ATR. Strong evanescent wave enhancement for TM and TE excitation was confirmed experimentally in the spectra of the evanescent wave reflectance τ_{meta}. This enhancement can be explained by resonant excitation of the waveguide modes. We calculated the dispersion relations of the modes, from which intensive confinement with ~ $\lambda/10$ is apparent. This confinement was contrasted with that of conventional diffraction-limited waveguide modes in a dielectric slab. The experimentally derived locations of the enhanced evanescent fields are consistent with the predicted excitation frequencies of the waveguide modes. This agreement is expected to be stronger if a stricter formalization is used that includes the effect of bianisotropy. Here, we excited intensively confined leaky modes. A possible way to realize the excitation of guided modes is to prepare a planar metamaterial structure on a substrate with a much lower refractive index such as a special type of polymer. These guided modes could be excited by simply using high-resistive silicon ATR prisms.

Flexible Metamaterial Absorbers for Stealth Applications at Terahertz Frequencies
Optics Express, 2012, 20(1): 635-643

Abstract: We have wrapped metallic cylinders with strongly absorbing metamaterials. These resonant structures, which are patterned on flexible substrates, smoothly coat the cylinder and

give it an electromagnetic response designed to minimize its radar cross section. We compare the normal-incidence, small-beam reflection coefficient with the measurement of the far-field bistatic radar cross section of the sample, using a quasi-planar THz wave with a beam diameter significantly larger than the sample dimensions. In this geometry we demonstrate a near-400-fold reduction of the radar cross section at the design frequency of 0.87 THz. In addition we discuss the effect of finite sample dimensions and the spatial dependence of the reflection spectrum of the metamaterial.

Conclusion: In summary, we have measured the bistatic radar cross section of a metal cylinder wrapped in a perfect metamaterial absorber. We have demonstrated that flexible metamaterial films with high resonant absorption can reduce the radar cross section of a metallic object by a factor of nearly 400. With metamaterials, it is possible to further tailor the response. For example, dual-frequency absorbers have been demonstrated and highlight that multiband reduction of the scattering cross section is feasible. In principle, it is even possible to create dynamically tunable stealth materials. Finally, given the scale invariance of metamaterials, we note that these results are relevant to other frequency ranges.

Single-Layer Terahertz Metamaterials with Bulk Optical Constants
Published in: *Physical Review B*, 2012, 85(3): 035112(6pp)

Abstract: We investigate the conditions under which single layer metamaterials may be described by bulk optical constants. Terahertz time domain spectroscopy is utilized to investigate two types of geometries, both with two different sizes of embedding dielectric—cubic and tetragonal unit cells. The tetragonal metamaterials are shown to yield layer dependent optical constants, whereas the cubic metamaterials yielded layer independent optical constants. We establish guidelines for when ε and μ can be used as material parameters for single layer metamaterials. Experimental results at terahertz frequencies are presented and supported by full wave three-dimensional electromagnetic simulations.

Conclusion: We have computationally and experimentally explored the conditions under which single layer metamaterials may be described by bulk optical constants. Two types of electric metamaterials were explored, both with two different sizes of embedding dielectric. The type 50 configuration was a cubic unit cell with a lattice parameter of 50 μm, and the type 15 configuration was a tetragonal unit cell, with dimensions $50 \times 50 \times 15\ \mu m^3$. The tetragonal metamaterials were shown to yield layer dependent optical constants, whereas the cubic type 50 metamaterials yielded layer independent optical constants. A Lorentz oscillator model was fit to type 50 metamaterials which permitted determination of the total number of charges involved in the primary metamaterial resonance.

Three-Dimensional Magnetic Terahertz Metamaterials Using a Multilayer Electroplating Technique
Journal of Micromechanics and Microengineering, 2012, 22(4): 045011(9pp)

Abstract: In the last decade, the development of metamaterials has led to exotic phenomena not shown in nature, including negative refractive index, invisibility cloaking and perfect absorption. To achieve these effects requires creating magnetically resonant subwavelength structures, since naturally occurring magnetism typically occurs at relatively low frequencies. In the far-infrared, or terahertz (THz), region of the electromagnetic spectrum, it is difficult to obtain a strong magnetic response from planar metamaterials at normal incidence. In this paper, multilayer electroplating is used to fabricate three-dimensional (3D) split-ring resonators that stand up out of plane. This enables the maximum coupling to the magnetic response at normal incidence. Characterization using THz time-domain spectroscopy indicates a strong magnetic resonance, and parameter extraction reveals a negative permeability from 1 to 1.3 THz with the minimal value of -2. The successful design, fabrication and characterization of 3D metamaterials provide opportunities to achieve different electromagnetic properties and novel devices in the THz range.

Conclusion: We have shown that SRRs enable specification of the permittivity and permeability to control and manipulate the EM THz radiation. A subwavelength SRR can couple to incident waves electrically, magnetically or in a combined way, thus exhibiting different EM properties. Utilizing MLEP technology, a series of 3D standing-up MM with different lengths of bars were fabricated successfully. In THz-TDS characterization with the magnetic field normal to the μ-SRR plane, the MM coupled strongly to magnetic field. By a simple rotation of 90°, almost 100% transmission was observed between 0.3 THz and 1.6 THz showing the strong polarization dependence of these structures. Furthermore, a significant resonant response near 1.2 THz was obtained and clearly demonstrates the effectiveness of these ‘magnetic atoms’. By decreasing the length of the bars, the resonance frequency blueshifts and the *Q*-factor increases. The effective parameters show that negative permeability values were achieved in a broad range from 1 to 1.3 THz. The successful design, fabrication and characterization of 3D MM offers considerable potential to achieve new EM functionality not previously possible at THz frequencies.

Time-Resolved Imaging of Near-Fields in THz Antennas and Direct Quantitative Measurement of Field Enhancements
Optics Express, 2012, 20(8): 8551-8567

Abstract: We investigate the interaction between terahertz waves and resonant antennas with sub-cycle temporal and λ/100 spatial resolution. Depositing antennas on a LiNbO3 waveguide enables non-invasive electro-optic imaging, quantitative field characterization, and direct measurement of field enhancement (up to 40-fold). The spectral response is determined over a bandwidth spanning from DC across multiple resonances, and distinct behavior is observed in the near- and far-field. The scaling of enhancement and resonant frequency with gap size and antenna length agrees well with simulations.

Conclusion: Our measurements have revealed key antenna features including the near-field spectral response, magnitude of the maximum field enhancement, and the time-dependent near-field profile in unprecedented detail. This will facilitate antenna design at all frequency ranges. Our methodology can also be applied to complex structures including metamaterials whose unique capabilities are based on near-field profiles and enhancements within antenna-like elements. In addition, enhancements of almost 40-fold and greater enhancements in future antennas with smaller gaps will enable new nonlinear THz phenomena to be explored. In spite of the fact that the enhanced field is tightly localized, the ability to probe exclusively in the gap region lets us take full advantage of the enhancement. High THz peak fields have been generated by other tabletop, ultrafast methods, but the THz output is typically a single-cycle pulse that has its energy distributed over a broad spectral range. The THz transients measured in our smallest antenna gaps have greater than 500 kV/cm peak-to-peak field strengths, comparable to those in strong single-cycle pulses. Our antenna-enhanced multicycle transients, however, have their energy concentrated in a much narrower spectral range, with spectral brightness exceeding that of the most intense broadband THz pulses. This spectral brightness makes it possible to strongly drive selected resonant transitions (electronic, vibrational, or rotational) for waveguide-based nonlinear spectroscopy and coherent control, while avoiding unwanted responses driven by extraneous frequency components. In the future, substantially larger E-fields could be produced by driving the antennas with stronger THz waves produced simply with additional optical pump pulse energy or with intensity-modulated optical pump waveforms tailored for efficient generation of multi-cycle THz pulses.

THz Near-Field Faraday Imaging in Hybrid Metamaterials
Optics Express, 2012, 20(10): 11277-11287

Abstract: We report on direct measurements of the magnetic near-field of metamaterial split ring resonators at terahertz frequencies using a magnetic field sensitive material. Specifically, planar split ring resonators are fabricated on a single magneto-optically active terbium gallium garnet crystal. Normally incident terahertz radiation couples to the resonator inducing a magnetic dipole oscillating perpendicular to the crystal surface. Faraday rotation of the polarisation of a near-infrared probe beam directly measures the magnetic near-field with 100 femtosecond temporal resolution and (λ/200) spatial resolution. Numerical simulations suggest that the magnetic field can be enhanced in the plane of the resonator by as much as a factor of 200 compared to the incident field strength. Our results provide a route towards hybrid devices for dynamic magneto-active control of light such as isolators, and highlight the utility of split ring resonators as compact probes of magnetic phenomena in condensed matter.

Conclusion: While our MM/TGG magneto-active devices have enabled direct imaging of the magnetic field with a resolution of l /200, numerous other possibilities are worthy of detailed exploration. This includes further optimization of the response to create compact devices such as dynamic Faraday isolators. In addition, SRRs provide a unique pathway to locally excite magnetic materials with well-defined high frequency fields to interrogate, for example, magnetic field induced switching or control of ferromagnets initiated by an applied picosecond electric field - that is, creating dynamic magneto-electric materials. This is essentially what we have accomplished at a basic level with our MM/TGG: it is the incident electric field which induces the SRR magnetic dipole that, in turn, induces the TGG Faraday rotation at near-infrared frequencies. Finally, recent advances in generating high-field THz pulses will be of interest for magnetic structures similar to what we have presented. For example, an incident THz pulse with a peak electric field of 1 MV/cm has a corresponding peak magnetic field of 0.3 Tesla. A field enhancement of 200 suggested by our numerical calculation would correspond to a local magnetic field of 60 Tesla of picosecond duration in the plane of the SRRs, sufficient to interrogate the dynamic magnetic properties of numerous materials.

Terahertz-field-induced Insulator-to-metal Transition in Vanadium Dioxide Metamaterial
Nature, 2012, 487(7407): 345-348

Abstract: Electron–electron interactions can render an otherwise conducting material insulating1, with the insulator–metal phase transition in correlated-electron materials being the canonical macroscopic manifestation of the competition between charge-carrier itinerancy and localization. The transition can arise from underlying microscopic interactions among the charge, lattice, orbital and spin degrees of freedom, the complexity of which leads to multiple phase-transition pathways. For example, in many transition metal oxides, the insulator–metal transition has been achieved with external stimuli, including temperature, light, electric field, mechanical strain or magnetic field. Vanadium dioxide is particularly intriguing because both the lattice and on-site Coulomb repulsion contribute to the insulator-to-metal transition at 340K. Thus, although the precise microscopic origin of the phase transition remains elusive, vanadium dioxide serves as a test-bed for correlated-electron phase-transition dynamics. Here we report the observation of an insulator–metal transition in vanadium dioxide induced by a terahertz electric field. This is achieved using metamaterial-enhanced picosecond, high-field terahertz pulses to reduce the Coulomb-induced potential barrier for carrier transport. A nonlinear metamaterial response is observed through the phase transition, demonstrating that high-field terahertz pulses provide alternative pathways to induce collective electronic and structural rearrangements. The metamaterial resonators play a dual role, providing sub-wavelength field enhancement that locally drives the nonlinear response, and global sensitivity to the local changes, thereby enabling macroscopic observation of the dynamics. This methodology provides a powerful platform to investigate low-energy dynamics in condensed matter and, further, demonstrates

that integration of metamaterials with complex matter is a viable pathway to realize functional nonlinear electromagnetic composites.

Conclusion: In summary, we have demonstrated a THz-driven insulator–metal phase transition and shown that in VO2 it is initiated by Poole–Frenkel electron liberation, followed by lattice equilibration on a picosecond timescale. Our work shows that metamaterial-enhanced high-field THz pulses can be used to study correlated-electron materials in a non-perturbative regime. The technique is extremely versatile, and can be used to study THz-induced phase transitions in other correlated materials and transition metal oxides (including high-Tc superconductors), as well as THz-induced changes in electronic properties more generally. The metamaterial design can be optimized to balance the requirements in any particular measurement for maximum field enhancement, bandwidth and mode volume. Magnetic-field enhancement can also be studied, as SRRs provide temporal and spatial separation of the peak electric and magnetic fields.

Three-dimensional Broadband Tunable Terahertz Metamaterials
Physical Review B - Rapid Communications, 2013, 87(16): 161104(4pp)

Abstract: We present optically tunable magnetic three-dimensional (3D) metamaterials at terahertz (THz) frequencies which exhibit a tuning range of ~30% of the resonance frequency. This is accomplished by fabricating 3D array structures consisting of double-split-ring resonators (DSRRs) on silicon on sapphire, fabricated using multilayer electroplating. Photoexcitation of free carriers in the silicon within the capacitive region of the DSRR results in a redshift of the resonant frequency from 1.74 to 1.16 THz. The observed frequency shift leads to a transition from a magnetic-to-bianisotropic response as verified through electromagnetic simulations and parameter retrieval. Our approach extends dynamic metamaterial tuning to magnetic control, and may find applications in switching and modulation, polarization control, or tunable perfect absorbers.

Conclusion: In summary, we have successfully fabricated and characterized broadband tunable 3D hybrid metamateirals at THz frequencies. With photoexcitation of silicon, we observed over 30% redshift of the resonant frequency, in agreement with numerical simulations. Parameters retrieval indicates that our 3D structure can be effectively switched from a mode with a strong magnetic response to a fully bianisotropic response. Our tunable 3D metamaterials can be potentially used as a tunable notch filter, high speed modulator. With proper design on the phase shift between two modes, artificial polarizers can also be realized.

Nonlinear Terahertz Metamaterials via Field-Enhanced Carrier Dynamics in GaAs
Physical Review Letters, 2013, 110(21): 217404(5pp)

Abstract: We demonstrate nonlinear metamaterial split ring resonators (SRRs) on GaAs at terahertz frequencies. For SRRs on doped GaAs films, incident terahertz radiation with peak fields of ~20–160 kV/cm drives intervalley scattering. This reduces the carrier mobility and enhances the SRR *LC* response due to a conductivity decrease in the doped thin film. Above ~160 kV/cm, electric field enhancement within the SRR gaps leads to efficient impact ionization, increasing the carrier density and the conductivity which, in turn, suppresses the SRR resonance. We demonstrate an increase of up to 10 orders of magnitude in the carrier density in the SRR gaps on semi-insulating GaAs. Furthermore, we show that the effective permittivity can be swept from negative to positive values with an increasing terahertz field strength in the impact ionization regime, enabling new possibilities for nonlinear metamaterials.

Conclusion: We have demonstrated that metamaterials enable strongly enhanced nonlinearities at terahertz frequencies. The present study illustrates strong THz-induced changes in the carrier mobility and density, yielding conductivity changes up to 10 orders of magnitude and large changes in THz transmission. As our proof-of-principle results demonstrate, it will be possible to create a host of nonlinear THz metamaterials which includes, as but one example, nonlinear absorbers for saturable absorber or optical limiting applications.

Decoupling Crossover in Asymmetric Broadside Coupled Split Ring Resonators at Terahertz Frequencies
Physical Review B, 2013, 88(2): 024101(5pp)

Abstract: We investigate the electromagnetic response of asymmetric broadside coupled split-ring resonators (ABC-SRRs) as a function of the relative in-plane displacement between the two component SRRs. The asymmetry is defined as the difference in the capacitive gap widths (∆g) between the two resonators comprising a coupled unit. We characterize the response of ABC-SRRs both numerically and experimentally via terahertz time-domain spectroscopy. As with symmetric BC-SRRs (∆g=0μm), a large redshift in the LC resonance is observed with increasing displacement, resulting from changes in the capacitive and inductive coupling. However, for ABC-SRRs, in-plane shifting between the two resonators by more than 0.375 L_o (L_o=SRR sidelength) results in a transition to a response with two resonant modes, associated with decoupling in the ABC-SRRs. For increasing ∆g, the decoupling transition begins at the same relative shift (0.375L_o), though with an increase in the oscillator strength of the new mode. This strongly contrasts with symmetric BC-SRRs, which present only one resonance for shifts up to 0.75L_o. Since all BC-SRRs are effectively asymmetric when placed on a substrate, an understanding of ABC-SRR behavior is essential for a complete understanding of BC-SRR based metamaterials.

Conclusion: In summary, we investigated the response of asymmetric BC-SRRs (ABC-SRRs) under lateral shift using THz-TDS and numerical simulations. We observe a transition from a one-resonance state to a two-resonance state for shift values larger than L_{shift}/L_o=0.375, where

L_o is the side length of an SRR. For lateral shifts lower than this value, the ABC-SRRs act as one coupled resonant element. Above this value, the component SRRs respond to incident radiation as separate, uncoupled resonators, as evidenced by the simulated on-resonance surface current densities. This behavior is consistent with the previously published results for symmetric BC-SRR structures and can be explained using similar conceptual models. As substrate-induced bianisotropy, fabrication error, and other effects can conspire to make symmetric BC-SRRs effectively asymmetric, these results provide a description of ABC-SRR behavior essential for complete understanding of BC-SRR based MMs.

Towards Dynamic, Tunable, and Nonlinear Metamaterials via Near Field Interactions: A Review
Journal of Infrared, Millimeter, and Terahertz Waves, 2013, 34(11): 709-723

Abstract: Metamaterials research continues to bear fruit in the form of novel devices and optics across the electromagnetic spectrum. This is especially true in the gigahertz, terahertz, and near infrared frequencies. Metamaterials also continue to be one of the fastest growing subdisciplines of anisotropy research, with most notable metamaterial advances based on inherently anisotropic designs. Despite significant progress, many challenges remain before fully dynamic, broad bandwidth, and nonlinear metamaterial devices become truly viable. We review the study of near field interactions, or coupling, in metamaterials with a focus on how manipulation of interactions in metamaterials has helped overcome some of the largest obstacles toward tunable metamaterials, broad bandwidth metamaterials, nonlinear metamaterials, and metamaterial experimental techniques.

Conclusion: The creation of metamaterials has brought great advances across the spectrum, especially at terahertz and gigahertz frequencies, and is one of the fastest growing fields in the study of anisotropy. However, many challenges and limitations remain before MM devices and techniques become commonplace at any frequency. We have reviewed near field coupling in metamaterials with a focus on addressing some of the major challenges in metamaterials research. In particular, the manipulation of MM coupling has brought about significant advances in the areas of frequency tunable and broad bandwidth metamaterials, nonlinear metamaterials, and MM based experimental techniques. The future for MM is, of course, exciting and unpredictable. It is clear, however, that controlling near field interactions in metamaterials will play an integral role in future advances in this fascinating field of research.

Optically Tunable Terahertz Metamaterials on Highly Flexible Substrates
IEEE Transactions on Terahertz Science and Technology, 2013, 3(6): 702-708

Abstract: We present optically tunable metamaterials (MMs) on flexible polymer sheets operating at terahertz (THz) frequencies. The flexible MMs, consisting of electric split-ring resonators (eSRRs) on patterned GaAs patches, were fabricated on a thin polyimide layer using

a transfer technique. Optical excitation of the GaAs patches modifies the metamaterial response. Our experimental results revealed that, with increasing fluence, a transmission modulation depth of ~60% was achieved at the LC resonant frequency of 0.98 THz. In addition, a similar modulation depth was obtained over a broad range from 1.1 to 1.8 THz. Numerical simulations agree with experiment and indicate efficient tuning of the effective permittivity of the MMs. Our flexible tunable device paves the way to create multilayer nonplanar tunable electromagnetic composites for nonlinear and multifunctional applications, including sensing, modulation, and energy harvesting.

Conclusion: A novel flexible tunable MM was fabricated employing a semiconductor transfer technique and characterized by optical-pump terahertz-probe spectroscopy. The total thickness of sample is 4.7 μm, equivalent to ~0.015 of the resonant wavelength at 0.98 THz. Our experimental results show that low-fluence photoexcitation of the GaAs layer yields a transmission modulation depth of 60%. Numerical simulations agree with the experimental results and reveal the details of the modulation of the effective permittivity. Our flexible tunable device enables the creation of tunable multilayered nonplanar electromagnetic composites and potential sensing applications on nonplanar structures.

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MATERIALS AND MECHANICS OF METAMATERIAL ENHANCED MEMS FOR TERAHERTZ TECHNOLOGY

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Xin Zhang

Program Manager
The AFOSR Program Manager currently assigned to the award

Dr. B. L. ("Les") Lee, Byung.Lee@us.af.mil

Reporting Period Start Date

09/30/2009

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Abstract

Recently, artificially structured electromagnetic materials have become an extremely active research area because of the possibility of creating materials which exhibit novel electromagnetic responses not available in natural materials, such as negative refractive index. Such electromagnetic composites, often called metamaterials, are sub-wavelength composites where the electromagnetic response originates from oscillating electrons in highly conducting metals such as gold or copper allowing for a design specific resonant response of the electrical permittivity or magnetic permeability. This is especially important for the technologically relevant terahertz frequency regime where there is a strong need to create components to

realize applications ranging from spectroscopic identification of hazardous materials to noninvasive imaging. Over the past years, the PIs and their team at Boston University have worked on fundamental research combining metamaterials with MEMS (microelectromechancial systems or microsystems) at terahertz frequencies. The team has developed metamaterial enhanced resonant detectors with a simple fabrication process for active terahertz sensing and detection applications. The team has published papers in top journals including Nature, Physical Review Letters, and Advanced Materials. Their work has also been highlighted by Science, Nature, and MRS Bulletin. In addition, two PhD students have won Boston University Best Dissertation Awards through working on this project.

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Archival Publications (published) during reporting period:

Title: Comparison of Birefringent Electric Split-Ring Resonator and Meanderline Structure as Quarter-Wave Plates at Terahertz Frequencies
* With A.C. Strikwerda, K. Fan, H. Tao, D.V. Pilon, R.D. Averitt
* Published in: Optics Express, 2009, 17(1): 135-149

Title: Reconfigurable Terahertz Metamaterials
* With H. Tao, A.C. Strikwerda, K. Fan, W.J. Padilla, R.D. Averitt
* Published in: Physical Review Letters, 2009, 103(14): 147401(4pp)

Title: A Dual Band Terahertz Metamaterial Absorber
* With H. Tao, C.M. Bingham, D.V. Pilon, K. Fan, A.C. Strikwerda, D. Shrekenhamer, W.J. Padilla, R.D. Averitt
* Published in: Journal of Physics D: Applied Physics, 201, 43(22): 225102(5pp)

Title: Metamaterial Silk Composites at Terahertz Frequencies
* With H. Tao, J.J. Amsden, A.C. Strikwerda, K. Fan, D.L. Kaplan, R.D. Averitt, F.G. Omenetto
* Published in: Advanced Materials, 2010, 22(32): 3527-3531

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* With H. Tao, A.C. Strikwerda, M. Liu, J.P. Mondia, E. Ekmekci, K. Fan, D.L. Kaplan, W.J. Padilla, R.D. Averitt, F.G. Omenetto
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* With H. Tao, W.J. Padilla, R.D. Averitt
* Published in: IEEE Journal of Selected Topics in Quantum Electronics, 2011, 17(1): 92-101

Title: MEMS Based Structurally Tunable Metamaterials at Terahertz Frequencies
* With H. Tao, A. Strikwerda, K. Fan, W.J. Padilla, R.D. Averitt
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Title: Microwave and Terahertz Wave Sensing with Metamaterials
* With H. Tao, E.A. Kadlec, A.C. Strikwerda, K. Fan, W.J. Padilla, R.D. Averitt, E.A. Shaner
* Published in: Optics Express, 2011, 19(22): 21620-21626

Title: Electromagnetic Composite-Based Reflecting Terahertz Waveplates
* With A.C. Strikwerda, R.D. Averitt, K. Fan, G.D. Metcalfe, M. Wraback
* Published in: International Journal of High Speed Electronics and Systems, 2011, 20(3): 583-588

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* With Y. Minowa, M. Nagai, H. Tao, K. Fan, A.C. Strikwerda, R.D. Averitt, K. Tanaka
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* With K. Iwaszczuk, A.C. Strikwerda, K. Fan, R.D. Averitt, P. Uhd Jepsen
* Published in: Optics Express, 2012, 20(1): 635-643

Title: Single-Layer Terahertz Metamaterials with Bulk Optical Constants
* With W.-C. Chen, A. Totachawattana, K. Fan, J.L. Ponsetto, A.C. Strikwerda, R.D. Averitt, W.J. Padilla
* Published in: Physical Review B, 2012, 85(3): 035112(6pp)

Title: Three-Dimensional Magnetic Terahertz Metamaterials Using a Multilayer Electroplating Technique
* With K. Fan, A.C. Strikwerda, R.D. Averitt
* Published in: Journal of Micromechanics and Microengineering, 2012, 22(4): 045011(9pp)

Title: Time-Resolved Imaging of Near-Fields in THz Antennas and Direct Quantitative Measurement of Field Enhancements
* With C.A. Werley, K. Fan, A.C. Strikwerda, S.M. Teo, R.D. Averitt, K.A. Nelson
* Published in: Optics Express, 2012, 20(8): 8551-8567

Title: THz Near-Field Faraday Imaging in Hybrid Metamaterials
* With N. Kumar, A.C. Strikwerda, K. Fan, R.D. Averitt, P.C.M. Planken, and A.J.L. Adam
* Published in: Optics Express, 2012, 20(10): 11277-11287

Title: Terahertz-field-induced Insulator-to-metal Transition in Vanadium Dioxide Metamaterial
* With M. Liu, H.Y. Hwang, H. Tao, A.C. Strikwerda, K. Fan, G.R. Keiser, A.J. Sternbach, K.G. West, S. Kittiwatanakul, J. Lu, S.A. Wolf, F.G. Omenetto, K.A. Nelson, R.D. Averitt

* Published in: Nature, 2012, 487(7407): 345-348

Title: Three-dimensional Broadband Tunable Terahertz Metamaterials
* With K. Fan, A.C. Strikwerda, R.D. Averitt
* Published in: Physical Review B - Rapid Communications, 2013, 87(16): 161104(4pp)

Title: Nonlinear Terahertz Metamaterials via Field-Enhanced Carrier Dynamics in GaAs
* With K. Fan, H.Y. Huang, M. Liu, A.C. Strikwerda, A. Sternback, J. Zhang, X. Zhao, K.A. Nelson, R.D. Averitt
* Published in: Physical Review Letters, 2013, 110(21): 217404(5pp)

Title: Decoupling Crossover in Asymmetric Broadside Coupled Split Ring Resonators at Terahertz Frequencies
* With G.R. Keiser, A.C. Strikwerda, K. Fan, V. Young, R.D. Averitt
* Published in: Physical Review B, 2013, 88(2): 024101(5pp)

Title: Towards Dynamic, Tunable, and Nonlinear Metamaterials via Near Field Interactions: A Review
* With G.R. Keiser, K. Fan, R.D. Averitt
* Published in: Journal of Infrared, Millimeter, and Terahertz Waves, 2013, 34(11): 709-723

Title: Optically Tunable Terahertz Metamaterials on Highly Flexible Substrates
* With K. Fan, X. Zhao, J. Zhang, G.R. Keiser, H.R. Seren, G.D. Metcalfe, M. Wraback
* Published in: IEEE Transactions on Terahertz Science and Technology, 2013, 3(6): 702-708

Changes in research objectives (if any):

N/A

Change in AFOSR Program Manager, if any:

N/A

Extensions granted or milestones slipped, if any:

N/A

AFOSR LRIR Number

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Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Non-Military Government Personnel Costs			
In-house Contractor Costs			
Travel (Be Specific)			
Training (Be Specific)			

Supplies			
Other Expenses (Be Specific)			
Total Resource Requirements			

Report Document

Appendix Documents

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